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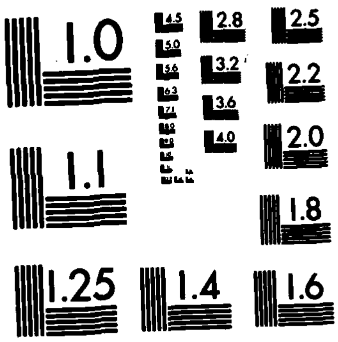

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A summary is presented of the major findings of a program whose objective was to investigate the phenomenon of preferential heat generation around damaged regions in materials subjected to mechanical vibrations and to develop an understanding of the mechanisms involved in this process. Vibrothermography is a nondestructive inspection technique based upon the utilization of this phenomenon. It has been found that this technique has

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20. ABSTRACT, cont'd.

much potential for inspecting composite materials. A significant amount of knowledge has been gained concerning the nature of the heat generation process and the relation of the frequency dependence of the heat patterns to the mechanical excitations.

Statement of Research Program

Vibrothermography is a nondestructive testing technique which utilizes a combination of mechanical vibrations and real-time video-thermography to investigate the internal state of damage in materials. The basic concept was discovered in our laboratory at Virginia Tech. It was observed that mechanical vibrations of various types, when introduced into a specimen, caused the preferential dissipation of energy into heat around internal discontinuities. This technique is unique in its ability to characterize complex damage states (such as develop, for example, during the fatigue of composite materials) in a manner which is directly related to the mechanics of the defect formation and of the defect state. Furthermore, the technique has the potential to be used as a quantitative nondestructive measure of the severity and distribution of the defects.

This research program was begun to specifically address the question of how heat is generated in damaged materials under vibratory excitation, and to develop an understanding of the mechanisms involved in those processes. An attempt was to be made to establish the physical parameters which control the heat generation processes, in order to enhance the efficiency of developing test methods (and choosing materials) based upon vibrothermography. In addition, the program attempted to further develop the general method of vibrothermography for a few select applications of particular importance. To be more specific, the objectives of this investigation were originally stated as follows:

1. To determine the mechanisms which are responsible for heat evolution in mechanically loaded systems and to establish an understanding of the corresponding heat

development processes, especially in the neighborhood of material defects or irregularities.

2. To determine the physical parameters which control the processes established in objective 1.

3. To develop the philosophy and techniques for the application of vibrothermography to practical situations and to establish the limitations of the method.

The approach which was used to achieve our objectives was to conduct a systematic investigation, mostly experimental in nature, wherein certain variables were controlled and the resulting response was noted. Strain rate, stress state, defect type and shape, material type and excitation history were controlled and varied to establish the mechanisms of heat generation and to determine the limitation of the method. A philosophy and understanding of these effects were sought so that results could be extended to situations which are not specifically addressed in our program. The first concern of our approach was to establish the basic nature of the vibrothermography effects and to develop an understanding and description of those effects. That understanding was tested by selecting several practical situations to examine and by comparing the results with our expectations.

Summary of Important Results

The first major objective of this research program was to determine the mechanisms of heat evolution responsible for the development of the observed thermographic heating patterns in the vicinity of damaged regions. Before this objective can be reached, it is necessary to establish in general the heat evolution mechanisms in mechanically loaded systems. This objective was studied early and results were reported in Ref. 2 listed under Publications and Technical Reports Published. We found, to begin with, that the present state of the field of study concerning energy dissipation in solid materials is disjunct. In fact, in our opinion, the lack of a unified approach to the field has been a serious impediment to progress. In any case, examination of the literature for mechanisms which may be responsible for heat generation in the vibrothermography technique led to some conclusions about which mechanisms were <u>not</u> responsible. For example, the dissipative mechanisms associated with anelasticity are not of practical importance to the vibrothermography technique because of the low amount of heat such mechanisms produce and the low frequencies at which these mechanisms are excited. Also, examination of the literature led to some conclusions concerning which parameters are important to stress related thermal emission processes. An example here is the fact that thermal conductivity of the material interrogated plays a dominant role in the thermographic patterns developed while the geometry dependence (region size, for example) plays a more minor role.

The application of the vibrothermographic technique is affected by our practical ability to observe and produce heat images. We have found that, as expected, the magnitude of the temperature difference between

heat generating regions and non-heat generating regions is three orders of magnitude greater for insulators than for good conductors. Second, the sharpness of the temperature gradients is also different, i.e., for good conductors the distance over which the temperature change is spread is less. Both of these factors affect the acuity of the heat image developed. Details of the dependence of image acuity upon these factors were presented in Ref. 2. For stress related thermal emission to be used to locate material defects and characterize the local response in the neighborhood of a defect or flaw, only certain mechanisms are of practical interest. We may categorize those mechanisms as anelastic effects, viscoelastic effects and structural dissipation. The only anelastic effect which is possibly important to the vibrothermographic technique is the dissipation produced by relaxation mechanisms in long chain molecules. If history-dependent behavior (viscoelastic effects) is present, especially plastic deformation and localized slip, very large temperature differences can be produced in both good and poor conductors. Structural dissipation on the local level due to the interference or interaction of two surfaces which rub, flap or pound against each other under cyclic excitation may also produce considerable heating. Our experimental work has indicated that the latter two mechanisms are typically acting concurrently, especially in composite materials and are almost, if not entirely, totally responsible for the observed heat patterns (Ref. 3).

One of the more efficient heat-producing mechanisms, according to our experimental observations, is plastic deformation in metals or polymers. For example, a bar of aluminum cycled in tension-compression fatigue to load levels above the yield stress reached a steady state

temperature 140°C above ambient. A polycarbonate specimen, loaded quasi-statically at a slow rate developed deformation bands which slowly progressed through the specimen. The temperature in these deformation bands exceeded 16°C above that in undeformed regions of the bar (Ref. 3). On the other hand, in composite materials, we have made an especially large number of experimental observations under both large amplitude, fatigue loadings and low amplitude, high frequency loadings. In these materials, temperature differences in excess of 30°C have developed in regions where internal surfaces such as delaminations exist. These regions develop heat by a combination of structural dissipation and viscoelastic effects. We have been unable, as yet, to separate the relative proportion of heating due to each mechanism. However, it appears as if each mechanism is indeed acting in composite materials and each adds substantially to the observed heat pattern. This conclusion is based upon a series of experimental observations made in our laboratory, as discussed further in subsequent paragraphs.

A major difficulty ensuing from the lack of an appropriate physical model for detailing the phenomenon of vibrothermography is the degree to which correct conclusions can be drawn from experimental observations. On the other hand, in order to develop the model, one needs to base the requirements for the model upon physical observations. For example, in an early paper (Ref. 5), we were led to state the conclusion that the thermal patterns produced in the vibrothermography technique were independent of resonances of the specimen-shaker system. Rather, we were led to believe, based upon experimental observations made up to that time, that the developed thermal patterns were caused by local resonances in the neighborhood of damage existing in composite

specimens. These local resonances would depend upon the local geometry and stress fields in the damaged region and hence would be affected little by any changes in system resonances. More recent observations (Ref. 12) have forced us to modify this position. The recent observations indicate that the heat patterns produced are dependent upon both local and system resonances. In particular, the frequencies of vibration at which a local damaged region becomes delineated by development of thermal patterns appear to be frequencies of natural resonances of the specimen. There is an interaction between the presence of damage and the resonating condition of the specimen which causes heating in the region of damage.

This frequency related behavior of laminated fiber reinforced composite structures with delaminations during vibrothermographic inspection has been studied thoroughly (Ref. 12). Two models were proposed to explain the frequency-related heat patterns developed during vibrothermography. First, a local resonance model was postulated using an analytical dynamic examination of a delamination in an infinite medium. In this case, the delamination was modeled as two anisotropic plates, one on either side of the delaminated region, tied together along the boundary of the delamination. The natural modes of resonance for these plates were then calculated and used to predict frequencies of heating. Second, a structural resonance model was proposed. Here, the natural modes of resonance were calculated for the entire specimen. For the first model, it was assumed that heating would preferentially occur at the delamination site when the local plates began resonating. For the second model, it was assumed that heating would occur preferentially when local strain fields increased in value due to structural resonating

conditions. That is, the frequency dependence of the heating is assumed to occur because the stress-amplitude in the region of the damage is dependent on the resonance frequencies of the structure. During a structural resonance, a damage region may or may not develop heating, depending upon the location of the damage in the structure. The standing waves or mode shapes in the structure determine where the strain energy is distributed and hence determine if a particular damage region in a certain location will develop heating to an extent detectable by the thermographic camera.

Both of the postulated models were tested experimentally and compared to the predictions (Ref. 12). Composite panels having thicknesses of two plies, with delaminations between the plies, developed heat pattern-frequency relations as predicted by the local resonance model. However, thicker laminates did not develop heat patterns at predicted frequencies. For these thicker laminates, the heat patterns developed at frequencies corresponding to the structural resonance model. The question as to why the thinner and thicker panels respond differently has not as yet been answered.

A large number of experiments conducted throughout this program have produced results which continue to indicate the usefulness and advantages of vibrothermography as a nondestructive inspection technique. Thermographic methods are field techniques and hence can interrogate large areas of structural components or even large structures. This is in contrast to most of the more widely used nondestructive test methods which interrogate such small regions of material as to be practically point techniques. Furthermore, little preparation is required to perform the vibrothermographic test.

Vibrothermography is especially advantageous for locating delaminations in composites. We have used it for detecting damge caused by static, fatigue, and impact (dynamic) loadings. Evidence has also been collected which shows that the maximum temperature observed during the vibrothermographic inspection of graphite epoxy laminates increases with the size of the damaged region caused by impact loading (Ref. 12). At this time, knowledge of failure mechanisms in composite materials is insufficient to be able to relate the size of damage to mechanical strength. However, other work in our laboratory has shown a direct relation between laminate stiffness and the degree of damage. Thus, further testing should lead to a relation between the degree of heating as observed in the vibrothermographic technique and laminate stiffness.

List of Publications and Technical Reports Published

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12. S. S. Russell, "An Investigation of the Excitation Frequency Dependent Behavior of Fiber Reinforced Epoxy Composites During Vibrothermographic Inspection," Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA, Nov. 1982.

List of Participating Scientific Personnel

The following individuals participated in this project as Principal Investigators:

Professor Edmund G. Henneke, II
Professor Kenneth L. Reifsnider
Professor Wayne W. Stinchcomb

The following individual participated as a Graduate Research Assistant in this project, and, as a result of his work, wrote a dissertation and obtained a Ph.D. degree in Engineering Mechanics:

Dr. Samuel S. Russell

END